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Helicopter Control Systems: A History

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Introduction

THE history of helicopter control systems is presented first with regard to the development of the mechanical systems still found on most small helicopters. The second part of the paper discusses the development of electronic stabilization systems that have been found necessary for flying under instrument conditions and for performing challenging "high-gain" maneuvering tasks.

Mechanical Control Systems

Beginning

The first successful rotary-wing aircraft, the Cierva autogyro, built in 1923, was simply a modified airplane with an unusual wing that, even at very low forward speeds, would not stall. This "wing" had no power delivered to it, and the pilot had no control over it. That the rotor had an asymmetrical velocity field in forward flight was taken care of by a blade flapping motion about hinges at the blade roots. Such a rotor is a system in resonance with its rotational frequency. By the magic of physics, the blade could sense just how much to flap to change the local angles of attack to compensate for the asymmetrical velocity field. The pilot flew the aircraft with conventional airplane surfaces: elevator, rudder, and ailerons.

This was the configuration used until about 1933, when it became obvious that, although the rotor had no problem developing lift at low airspeeds, the effectiveness of the airplane control surfaces was less than desirable and some innovation was required.

The story is that Cierva was in London during a windy rainstorm and noticed how people were tilting their umbrellas to provide maximum protection. This gave him the inspiration for the "direct control" system, in which the rotor is mounted on a gimbal, and the gimbal can be tilted longitudinally and laterally by a control stick in the pilot's hand. Because the rotor thrust vector is perpendicular to its tip path plane, tilting the rotor produces roll and pitch moments about the center of gravity. With this breakthrough, the wings that had been used primarily to support ailerons could be eliminated, and the horizontal tail could be made without an elevator. Figure 1 shows the Cierva C.30 with its "hanging stick." Direct control was the preferred configuration for autogyros before World War II and is still used on some small gyroplanes.

Helicopters Are Different

During this period, the helicopter inventors had not been idle. However, in 1930, when D'Ascanio established a world helicopter record by flying half of a mile in 8 min, Cierva flew one of his autogyros from London to Paris at over 100 mph.

Whereas the autogyro was controllable with the gimbal device, it was not practical for helicopters, and so another system was invented spontaneously by a number of engineers as the logical way to account for the unequal aerodynamics on the rotor in forward flight and to provide roll and pitch control. "Cyclic pitch" was apparently first proposed by G. A. Crocco in 1906.

Mechanism

The key to cyclic pitch is the swashplate. Long before helicopters were imagined, it was used where a transfer of sliding motion was required between stationary and rotating components. One early application, patented in 1788, was the Watt flyball governor, which introduced the age of automatic feedback control. Figure 2 shows the swashplate as part of a helicopter control system.

Note that if the swashplate is perpendicular to the rotor shaft, the blade angle is constant around the azimuth, but if the swashplate is tilted, the blade pitch will go though one complete feathering cycle once every revolution. If the pilot pushes the cyclic stick forward, the swashplate is tilted forward, and because the pitch horn is attached to the swashplate 90 deg ahead, the blade has its pitch reduced when it is on the right side and increased when it is on the left. (Note that pitch horns are not as long on real helicopters as that shown in Fig. 2. The control system below the swashplate is rotated so that

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Fig. 1 Cierva direct control autogyro.

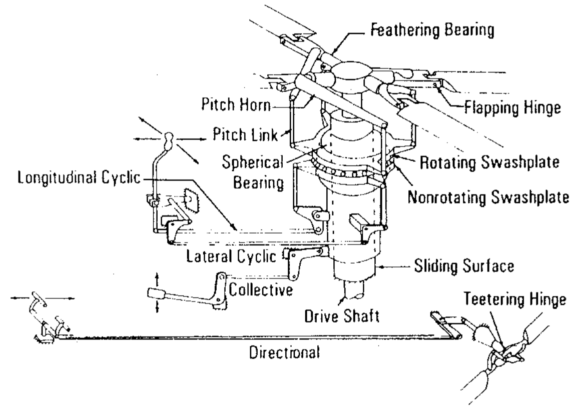

Fig. 3 Expanded helicopter control system.

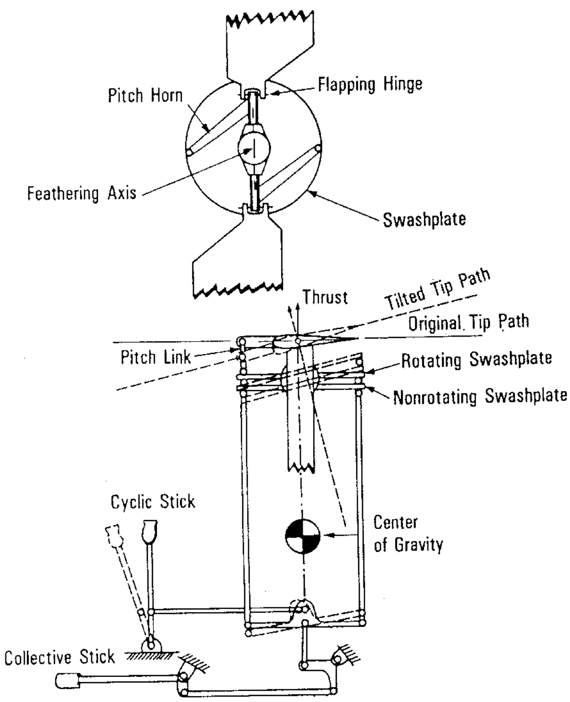

Fig. 2 Basic helicopter control system.

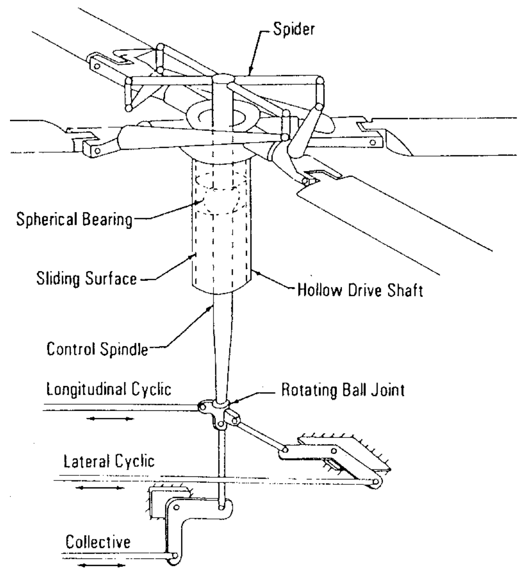

Fig. 4 Westland "spider" control system.

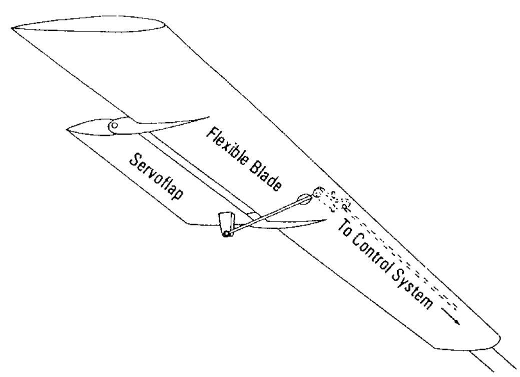

Fig. 5 Kaman servoflap.

the relationship between the cockpit control and the cyclic pitch is the same as just described.)

As a system in resonance, the rotor responds by flapping down over the nose, producing the nosedown moment about the center of gravity needed to tilt the entire aircraft to make the transition from hover to forward flight. This is shown by the dotted lines in Fig. 2. The roll control, of course, is exactly the same as pitch control, but is done with lateral movements of the cyclic stick. In either case, the thrust vector tilts in the same direction as the stick.

Besides maneuvering, the cyclic pitch can be used in steady flight to adjust the tip path plane with respect to the shaft. In this case, the pilot can mechanically change the angle of attack of the blades by the same amount that the flapping motion would have, thus eliminating flapping or leaving just enough to balance pitching and rolling moments due to fuselage aerodynamics or an offset center of gravity position.

It can be shown that centrifugal forces distributed over the blade put the feathering motion into resonance with the rotational velocity so that only very small inertial forces are developed in the cyclic control system.

A more detailed view of the helicopter control system is given in Fig. 3. The tail rotor system is also shown in Fig. 3. The pedals control the tail rotor collective pitch and are set up the same as those on an airplane: To turn to the right, press on the right pedal. The tail rotor has no cyclic pitch system, and so it adjusts itself by flapping, just as Cierva's original rotor did. Conventional travels for the various cockpit controls are ± 8 in. for the cyclic stick, 12 in. for the collective, and ± 3 in. for the pedals.

Alternate Systems

Instead of a swashplate, helicopters designed by Westland use the "spider system" shown in Fig. 4. Here, a single rotating ball joint transfers the motion between the stationary and rotating systems. Another concept, used by Kaman and shown in Fig. 5, does not change the pitch at the blade root. Instead, it relies on an outboard-mounted "servoflap" that can be deflected for both collective and cyclic pitch. When the trailing edge of the flap goes up, it produces a download at the blade's trailing edge that twists the flexible blade nose up. Thus, the servoflap is using "reverse psychology" to control the blade.

Sikorsky's Problem

Igor I. Sikorsky knew about cyclic pitch and tried to use it initially on his VS-300 helicopter. He may have been a genius, but he was a hard-headed genius. He had been building airplanes for a long time and knew that if you wanted to roll to the right, you decreased the lift on the right wing and increased it on the left. He, therefore, "knew" that this should also work on a rotor.

He held to this belief despite of being told about the 90-deg displacement between input and output on the rotor by others on his staff, including his cousin, Igor A. Sikorsky. Thus, the original VS-300 was misrigged by 90 deg and proved impossible to fly.

To solve this dilemma, Sikorsky temporarily abandoned cyclic pitch and achieved pitch and roll control with two boom-mounted horizontal tail rotors. This system flew for about a year until cyclic pitch was returned with the correct phasing.

Although the two horizontal tail rotors resulted in an awkward configuration, they did provide large damping in roll and pitch. It is probably for this reason that two U.S. Army autogyro pilots and Charles Lindbergh were able to learn to fly the one-man VS-300 with just minutes of instruction from Sikorsky as he stood on the tarmac beside them. They could soon hover successfully and make slow circuits of the field. (At this stage, the VS-300 could not fly forward very fast.) Today, most new helicopter pilots need several hours of dual instruction to achieve this level of proficiency.

Application to Hingeless Rotors

The use of cyclic pitch allows a rotor to be designed without mechanical flapping hinges. This was demonstrated on an autogyro in 1939 by E. Burke Wilford and was later exploited by Hiller on his coaxial design and by Lockheed for its helicopters. By the use of a cyclic pitch to compensate for the asymmetrical velocity distribution in forward flight, a "rigid rotor" becomes practical.

Unstable Helicopter and What to Do About It

The basic helicopter is unstable in hover. The reason can be traced to the rotor's tendency to flap back as forward speed is increased. This produces a noseup moment about the center of gravity. When the equations of motion are solved for the two degrees of freedom concerning forward translation and pitch rate, it will be found that the roots represent an unstable oscillation. For a typical helicopter, the period is about 20 s, and the time to double amplitude is about 10 s. By a pendulum analogy, the helicopter is swinging from a support about 30 blade lengths above it with a negative damper.

Step-by-Step

The instability phenomenon may be followed by first picturing a helicopter hovering in calm air, when, for some reason, it is nosed down slightly and the pilot does nothing with the controls. The resulting sequence of events is shown in Fig. 6.

1) At start, the forward tilt of the rotor produces a forward acceleration.

2) At 1 s, the helicopter is moving forward and, as the rotor flaps back with respect to the shaft, it produces a noseup pitching moment.

3) At 3 s, maximum noseup flapping and pitch acceleration occur. Pitch damping begins to reduce flapping.

4) At 5 s, maximum forward speed is attained. The fuselage is coming through the horizontal attitude with a noseup pitching velocity.

5) At 6 s, flapping changes from noseup to nosedown due to pitch damping. The pitch acceleration becomes negative, but pitch rate is still noseup. Forward speed begins to decay due to the noseup attitude of the rotor's tip path plane.

6) At 9 s, the forward speed is reduced to zero by the aft tilt of the rotor. However, the fuselage still has some residual noseup pitching velocity due to its inertia, and it is tilted further noseup than it was nosedown at the start.

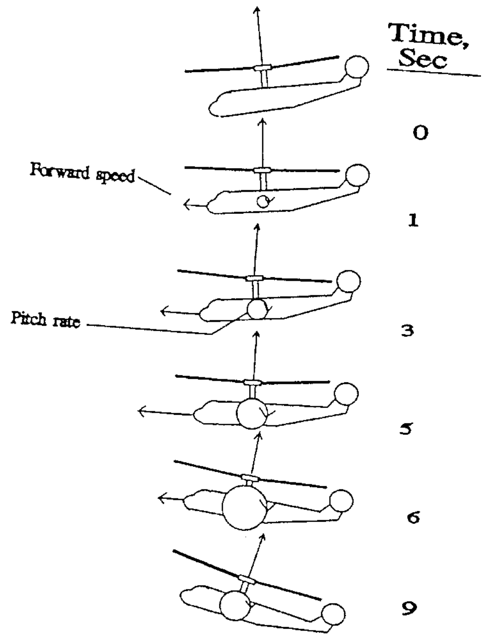

Fig. 6 Hover instability.

What It Means

That the helicopter has a greater pitch angle when the velocity goes to zero than when it began means that the sequence will start all over, going backward with greater acceleration than it had originally. This is the sign of an unstable system.

The combination of instability, the relative long time to achieve a response to a control motion, and the requirement to control the aircraft in six degrees of freedom presents a formidable challenge to the first-time helicopter pilot. (An oft-quoted analogy is that flying an airplane is like riding a bicycle, but hovering a helicopter is like riding a unicycle.)

Doing Something About It

Some early developers saw the poor flying qualities of a hovering helicopter as a great detriment to their acceptance and, thus, invented ways of helping the pilot. These all successfully used mechanical stabilizing systems based on external gyros. Three of these are shown in Fig. 7.

Why do we not see these pilot-friendly systems on modern helicopters? There are two reasons. The first is that once a pilot masters the hover task, that pilot is comfortable enough that there is little motivation to make it easier. Trying to convince the pilot otherwise is like trying to convince bicycle riders that they should have stuck to the tricycles of their childhood. An illustration of this mindset was illustrated by the remark of a U.S. Army helicopter pilot after his first flight in the Lockheed prototype: "If every private and general can fly this bird, who needs me?"

The second reason for the demise of the mechanical stability systems has been the development of electronic stabilization systems, which are discussed in the second part of this paper. For missions in which improved flying qualities are important, they can now be achieved with no aerodynamic drag and less weight than the mechanical systems, although at a higher cost.

Adding Muscle

On the small, original helicopters, all of the cockpit control forces due to aerodynamic and dynamic effects at the rotor hub were modest and could be handled by a pilot without any help. As helicopters got bigger, so did the forces. The airplane people had already faced similar problems and had developed hydraulic boost systems that, with relatively small changes, could be adapted to helicopters.

The first ones used a single hydraulic system with irreversible actuators installed, such that forces coming down from the rotor were reacted on the structure. They also included a bypass system that allowed the pilot to fly with the boost off, but with much higher

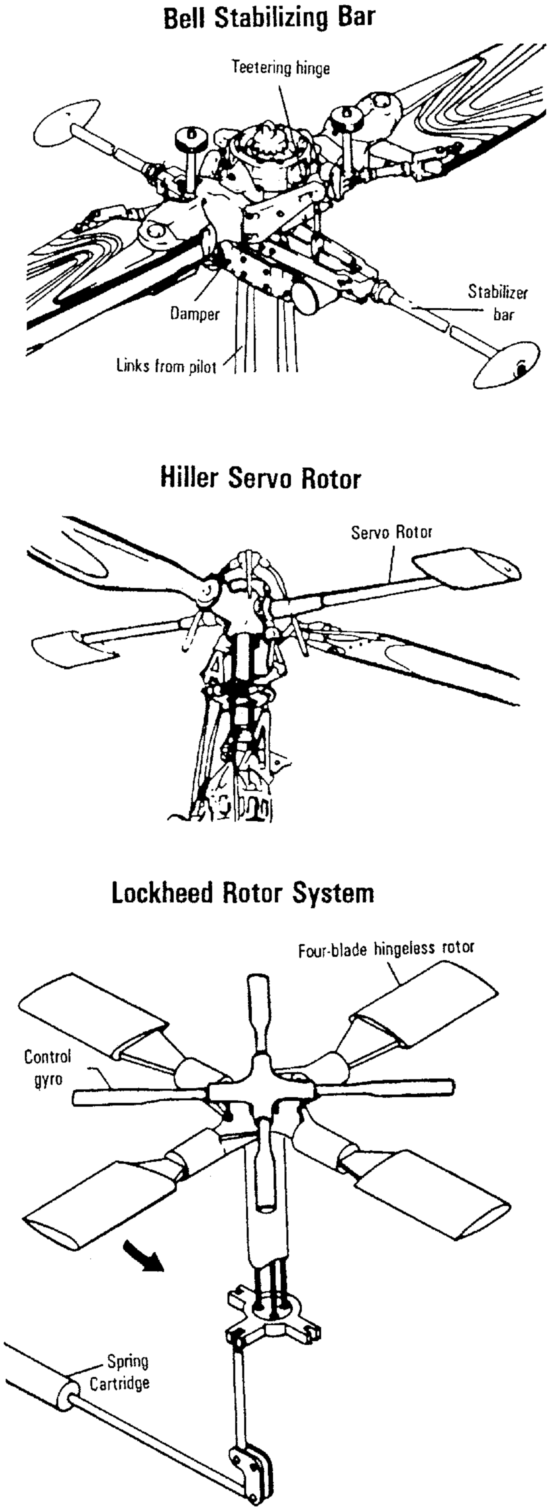

Fig. 7 Three gyro-based stability augmentation systems.

cockpit loads, much like the power-steering system in your car. Such a system is shown in Fig. 8.

Feel and Trim

With irreversible control actuators, the pilot is only moving low-friction servovalves with the cockpit controls. The pilot gets no feel from the control displacement, and, were the pilot to release a control, it might fall over due to its own weight. To remedy this, control centering and artificial feel are built into the cyclic control system and sometimes the pedals, whereas the collective system is usually equipped only with an adjustable friction device and a helper spring.

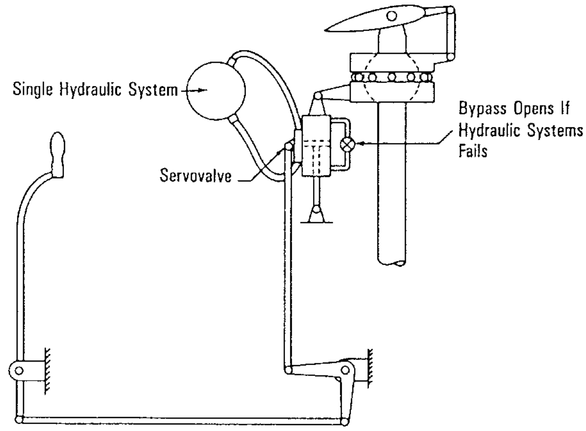

Fig. 8 Hydraulically boosted system.

Although pilots differ in what they consider to be an optimum control feel, most modern helicopters have a longitudinal cyclic pitch gradient of 1–4 lb/in., with the lateral system somewhat less in recognition of the relative strength of the arm in the two directions. This is part of what is called "control harmony." In addition to the gradient, the control should have a definite "detent" position that requires some force to initially move or "breakout." The detent can be achieved by preloading two springs against each other in a cartridge.

The gradient and the detent ensure that if the control is moved and then released, it will return to its original position. However, if the pilot has deliberately changed the flight condition, it is desired that the control stay in its new position. For this reason, it must be possible to relocate the detent reference position so that, at the new trim point, the stick will again hold its position.

There are two types of trim adjustments on modern helicopters. On one, a magnetic brake is used to fix the anchor point of the feel spring to structure. The "mag brake" contains a special fluid that freezes on application of an electric potential and relaxes when the voltage is cut off. When the pilot pushes a switch on the cyclic stick, the brake unfreezes and the springs quickly reset to their zero-force point.

The other system uses electric motors driving screw jacks to adjust the anchor points in response to a button on the top of the cyclic stick.

Even with irreversible controls, pilots are reluctant to let go of the control sticks any more than necessary, and so both the cyclic and collective sticks are festooned with an array of switches and buttons to allow a number of tasks to be performed with thumbs and fingers. Besides trimming the control forces, the pilot can transmit on the radio, talk on the intercom, use a searchlight, or fire weapons, all without removing his hands from the control sticks.

Stability Augmentation Systems

The hydraulic control actuators can easily be designed to incorporate an "electromechanical" valve that can be operated by electric signals coming from a computer that is fed by signals from rate and displacement gyros, the airspeed system, and any other sensor that can be used to improve flying qualities. The various strategies used will be discussed later.

More Muscle

As helicopters got bigger, the emergency mode of a single hydraulic system was no longer adequate, and so dual hydraulic systems were installed with great care to make them completely independent so that no single failure would disable both systems. Figure 9 illustrates this application to the Boeing Apache. On this aircraft, the authority of the stability augmentation is limited to $\pm 10\%$ of the actuator travel to guard against inadvertent hardovers due to computer failures.

One of the features of an electronic stabilization system is that it should distinguish between inputs coming from the external sensors and inputs coming from the cockpit controls so as to not fight the

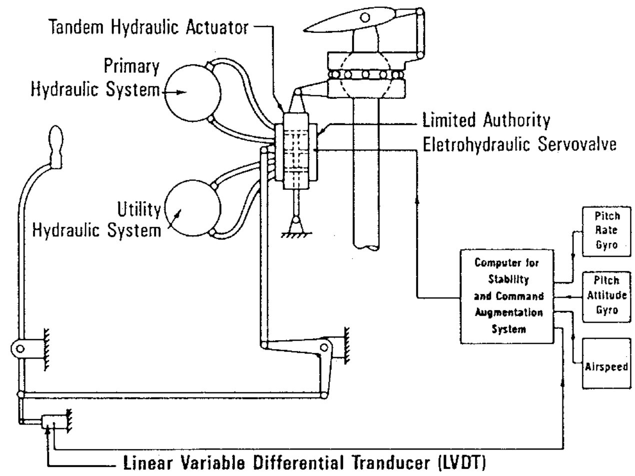

Fig. 9 Dual hydraulic system as used on Apache.

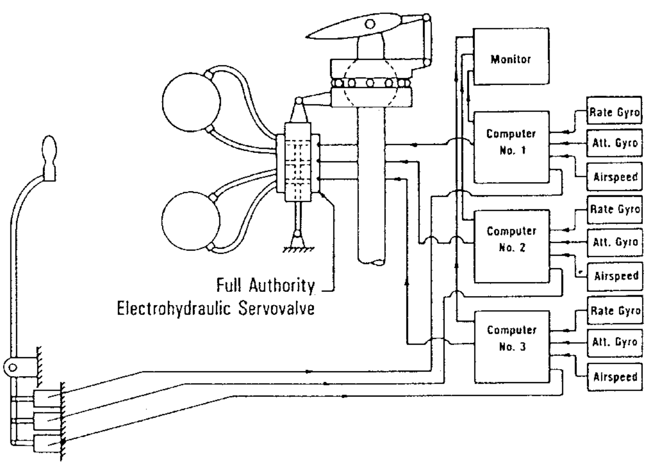

Fig. 10 Fly-by-wire system.

pilot. This is achieved by connecting a linear variable differential transducer (LVDT) to each control. Its feedforward input is used to minimize the signal from the rate gyros.

Once this system is incorporated, there is the possibility of using the LVDT to control the helicopter and to do away with the control rods between the cockpit and the actuators. This requires that the computer be capable of moving the actuators through their full travel. It is the "fly-by-wire" system used on the Comanche and the Osprey and illustrated in Fig. 10. Of course, to make these systems safe, they must be triply or even quadruply redundant. When the usual control rods between the cockpit and the actuators are eliminated, the fly-by-wire system provides a modest decrease in empty weight, but an immodest increase in cost.

Side-Arm Stick

The fly-by-wire system does, however, have the advantage of providing an option for improving cockpit geography. The usual central stick can be replaced by a side-arm stick, providing better visibility of the instrument panel. There have been several experimental installations where a single stick was used to provide all four controls: tilting for roll and pitch, twisting for directional, and vertical motion for collective. The Comanche designers have used the first three, but have chosen to use a conventional collective stick. The argument here is that the collective stick position is a fair representative of how much power is being used and, hence, gives the pilot a tactile indication of how much power is still available. The signals generated by the side-arm controller can either be based on small displacements or on forces sensed by strain gauges.

Another Consideration

One consideration of the fly-by-wire system is that those wires can act as antennas and generate false control pulses during flight in a thunderstorm. There is currently some activity underway to redesign these systems to safer "fly-by-light" using coded pulses of light traveling through optical fibers.

Analysis

As with all aircraft, there are six basic degrees of freedom that are of concern to the study of stability and control. However, because the blades of the helicopter are only loosely connected to the airframe, flapping introduces three more degrees of freedom: coning, longitudinal tilt, and lateral tilt (and, for some studies, the motion about the lead-lag hinge).

For most analyses, these extra degrees of freedom can be bypassed by what is known as the "quasi-static" assumption. This is based on the flapping response to control inputs or changes in angle of attack or forward speed being very rapid, in the neighborhood of one-fifth of a second for most helicopters. This allows the analyst to replace the rotor with a "black box" on top of the mast, which instantaneously develops forces and moments due to changes in control or the rotor environment.

This works for most analyses. It will cause trouble, however, for situations in which high-bandwidth electronic stabilization systems are part of the control system. In these cases, the full rotor degrees of freedom must be used, as will be discussed in the next section.

Development of Electronic Stabilization for Rotorcraft

Even in the early days of rotorcraft development, it was recognized that the path to good flying qualities would be through the application of electronic feedback.[1] The first flights were made in the fall of 1950 with the experimental prototype of the Piasecki HUP-1 equipped with a Sperry A-12 Autopilot designed for fixed-wing aircraft. After a total adjustment time of 2 h and 34 min, satisfactory stabilization and response characteristics were obtained throughout the speed range.[2] The craft was rated "easy to fly. . . and instrument flight no more difficult than a conventional airplane."[2] This was a parallel installation, as was common in fixed-wing practice at the time, in which the feedback signals also moved the control stick. This arrangement was considered to provide a desirable safety feature because a hardcover would be detected immediately by the pilot. Attitude changes were achieved with a separate controller. All production versions of the HUP-2 were equipped with an autopilot as the primary controller, and the tail surfaces were removed, although some reliability problems were encountered in the operational use of this system. Also, a Sikorsky H-19 was equipped with a Sperry A-12 during this same period. These early experiences were followed in 1954 by the introduction of automatic stabilization equipment (ASE) specifically designed for a rotorcraft [the S-58 (HSS-1) by Sikorsky]. This system was well ahead of fixed-wing practice at the time, employing a series arrangement for the feedback, with stabilization signals added to the control system downstream of the stick.[3] Vehicle attitude control was achieved directly through the control stick. The Sikorsky test pilot insisted that E.S. "Ted" Carter of Sikorsky, who was largely responsible for the engineering development, accompany him on the early flights. By 1957, the Sikorsky-developed four-channel ASE had accumulated more that 30,000 flight hours. Lessons learned during this period included that "mechanical design and quality control are more of a problem than electronics." Also, the view at Sikorsky was that ". . . electronic stabilization is now considered a basic part of the helicopter."[4] This system not only provided stability, but also improved the response characteristics of the helicopter. It was more than simply a device for stabilizing the aircraft in cruise. Bell Helicopter developed a control and stabilization system for its tandem design, the HSL-1 about this same time (1953–1954). Unmanned drone helicopters were flown by Kaman with the HTK-1, which had over 100 h of unmanned flight in 1955, and by Gyrodyne with the DSN-1, which made its first flight in August 1960.[5]

Conventional Systems

Other manufacturers, such as Hiller and Bell, that had depended on mechanical stabilizers (shown in Fig. 7) began using electronic feedback systems and eliminating the mechanical devices. Versions of the Hiller 12E-L dispensed with the Hiller control rotor and employed ASE equipment, as did the FH-1100 (Ref. 6). Other electronic systems were developed for the various versions of the Bell 47 and the Hiller H-23D. The Bell 206 (1966) and the Huey Cobra (1965) were the first Bell helicopters that did not incorporate the Young–Bell Bar. The Huey Cobra has a stability and control augmentation system, configured so that the rotorcraft response to disturbances could be designed separately from the response to pilot inputs by suitable use of feedforward and feedback.[7]

These developments have continued to the point where automatic stabilization systems are an essential component of most military helicopters and larger civil helicopters. The UH-60 Black Hawk and the AH-64 Apache have conventional mechanical control systems and use low-bandwidth stabilization systems with limited authority. The Black Hawk has a series stabilization system using lagged rate signals (dual channel, one analog, and one digital) as well flight-path stabilization (an autopilot) working in parallel. The AH-64 back-up control system is a digital, full-authority, fly-by-wire system. Choosing the configuration for good handling qualities is still considered a desirable goal especially in the civil market.[8]

Digital Systems

Advances in electronics and digital technology led to the integrated helicopter avionics system (IHAS) incorporating a triply redundant stability augmentation system (SAS) with a digital computer, developed for the Sikorsky CH-53 in 1963. The tactical air guidance system (TAGS) program demonstrated the capabilities of a flight control system based on these advances.[9] These programs were followed by the development of a fly-by-wire system in connection with the Heavy Lift Helicopter Program in 1974.[10,11] This full-authority redundant system was flight tested on a Boeing Model 347. The system demonstrated, among other attributes, the ability to control the longitudinal position of the helicopter very accurately, within a few inches. This was made possible in part by utilizing the unique nature of the tandem rotor control system, which permits separate control of longitudinal force and pitching moment.

High-Gain, High-Bandwidth Systems

For a highly maneuverable rotorcraft designed for demanding combat tasks, a very unstable vehicle with high-gain, high-authority stabilization and control systems may represent the best solution. The clear recognition that good stability and control characteristics, achieved electronically, play an essential role in helping the helicopter accomplish its many missions is contained in the current military handling qualities specifications.[12] Increases in the performance capabilities of the helicopter have led to expanding roles and missions, especially for military applications, and the requirement for a highly maneuverable, stealthy vehicle that can operate in all weather conditions has made high-gain, full-authority systems necessary.[13] Performing such tasks as aerial refueling, landing on small ships, or a decelerating approach in poor weather are difficult, if not impossible, to perform without stabilization and control augmentation. Required flight control system characteristics are defined in the current military handling qualities specifications. Different response characteristics are identified for different missions, tasks, and weather conditions. Many of these are not inherent in the rotorcraft and, thus, require feedback. An attitude command system is desirable for flight near hover, whereas a rate command system is preferred in cruise, for example.

Boeing also developed the Advanced Digital–Optical Flight Control System (ADOCS), a fly-by-light system that was installed in a UH-60 Black Hawk.[14] This was designed as a high-gain, full-authority, explicit model-following system. A goal of this design concept, similar to that for the Huey Cobra, was to separate the control response characteristics of the system from disturbance suppression using an explicit model-following system configuration. ADOCS was demonstrated successfully, although the overall system design gain was not achieved.[15] The system performed well, but did not live up to its expected potential. The effect of various high-frequency characteristics, such as the main rotor in-plane motions and actuator characteristics, had not been modeled in the design, illustrating the importance of accurate modeling of high-frequency characteristics for high-bandwidth control systems. In the development of modern high-gain systems that feature response characteristics essentially independent of flight conditions, it is essential that all of the high-frequency characteristics of the vehicle and its components be modeled accurately, so that the high gain necessary for good model-following performance can be obtained. It is not surprising that the suggestion of many years ago[16] that an inertia model of the rotorcraft is satisfactory for automatic flight control system design is no longer valid for high-bandwidth systems, although this assumption does indicate that modeling of the slow modes is of little importance because they are readily suppressed by feedback. For early helicopters, the body dynamics could be represented by inertial properties and with little or no hinge offset, and the main rotor flapping dynamics were weakly coupled and could be cascaded with the inertial model for low-bandwidth design. As long ago as 1953, it was recognized that the rotor flapping dynamics would be important for high-gain system design.[17] It was 30 years later when it was clearly shown that the in-plane (or lead-lag) degrees of freedom of the main rotor should be included in any high-gain control system design as well.[18] Fuselage motion feedbacks tend to destabilize the rotor, regressing lag motion. Modern vehicles with large hinge offset or hingeless rotors have increased coupling between the rotor and the body, resulting in a second-order initial response, especially on the roll axis.[19] Sensor dynamics, actuator dynamics, and digitizing effects can be equally important. The development of system identification techniques applicable to rotorcraft, along with the use of frequency response testing techniques, has led to considerable insight into rotorcraft dynamics and the modeling requirements for high-bandwidth systems.[20,21] Advances in digital system hardware and software with miniaturization and low weight make many things possible, limited primarily by complexity and cost. The RAH-66 Comanche flight control system, designed to meet the specifications of Ref. 12, uses an explicit model-following configuration with a number of selectable modes that provide additional stabilization and control augmentation as required.[22,23] The importance of accurate vehicle modeling high-gain model-following control system design is emphasized in Ref. 24.

Conclusions

A challenging problem for rotorcraft is the development of load or envelope limiting as part of an automatic control system. The many variables involved, including pilot technique, make it difficult to define the boundaries of the flight envelope of a helicopter. A high-*g* turn, for example, can produce many different loadings that depend in detail on how the vehicle is maneuvered.

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